Environmental policies analysis for CO2 emission reduction: evidence across countries 1980-2014

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Abstract

We employ a difference-in-difference regression model to analyse the efficiency of carbon taxation policy and its interaction with an Emission Trading System (ETS). We provide evidence for 26 of the most developed countries in the world in the period 1980-2014. Following the work of Dynarski [2004], Cameron et al. [2008, 2012] and Hoechle [2007], we compare the results under three methods of regression analysis. We confirm that carbon taxation has preformed well in the 35 years under observation in that they efficiently control CO2 emissions. We find that the longer duration a country uses carbon taxation, the greater the reduction in CO2 emissions. For the countries that use both an ETS and carbon taxation, we find an even more efficient CO2 emission reduction. The results are robust to heteroskedasticity, autocorrelation and cross-sectional dependence.

Keywords: Carbon Pricing Instruments, CO2 Emission Reduction, Difference-in-Difference Model, Robust Standard Errors, Cross-sectional Dependence, Few Clusters

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1 Introduction

Carbon taxation and Emissions Trading Systems (ETS) are generally considered to be efficient environmental policies to reduce CO2 emissions. However, in 2017, only 42 national and 25 subnational jurisdictions had some form of carbon pricing — either through an emissions trading scheme or a carbon tax. Instead, more countries have been using nuclear or renewable energies such as wind, solar, geothermal and biomass in the past decades to reduce CO2 emissions. Finland and Sweden are two of the very few countries that have both implemented a carbon tax and an ETS scheme (as both are in the EU-ETS Scheme). Moreover both countries also use nuclear and non-renewable energy sources. Data from these two countries demonstrate a clear and dramatic reduction in CO2 emissions. However, it is difficult to conclude whether the emission reduction results from carbon pricing instruments, the lower consumption of energy, intensity improvement or GDP reduction. In this article, we focus on carbon pricing instruments. We test the treatment effects of carbon taxation policy and a joint use of both taxation and ETS. We then determine whether they efficiently control CO2 emissions and which one has performed better. Our aim is to provide empirical evidence to encourage and support the implementation of carbon pricing instruments.

Many researchers have provided evidence of the effectiveness of carbon pricing instruments, both theoretically and empirically. For example, Newell et al. [2013] provide a clear summary of the carbon market performance in several countries. The existing empirical literature usually chooses a short time horizon. In this article, we try to include most developed countries (that satisfy our countries selection criteria for the difference-in-difference model) as possible and at the same time use a long time horizon to support our analysis. We employ a difference-in-difference regression model to analyse the efficiency of carbon taxation policy and its interaction with an ETS, as evidence for the most developed countries in the world over the period 1980-2014. As of December 2014, 17 countries had introduced carbon taxation as part of their emission reduction strategies. We include 11 of them – 64.1% in our analysis. The six carbon taxation users that are excluded are Latvia, Estonia, Slovenia, Iceland, Poland and Mexico. We drop the first four countries due to insufficient data.[1] We drop Poland and Mexico because of their lower levels of economic development. It finally leaves us with a 35-year panel data series across 26 countries. We include the shares of consumption of the different forms of energy usage as well as commonly used measures such as Gross Domestic Product based on Purchasing Power Parity per capita (GDP on PPP) , energy intensity (EI) as control covariates following Zakarya et al. [2015], Bruvoll and Larsen [2004], Lin and Li [2011], Scrimgeour et al. [2005], Song et al. [2015], Meng et al. [2013], Doda et al. [2012] and Liu et al. [2015], just list a few. To

[1] Hoechle's (2007) approach can handle missing values problem. However, the authors prefer the balanced data.

deal with few clusters, we use a country specific bootstrap following the work of Cameron et al. [2008, 2012] and make adequate use of bootstrap replicates.[2]. We find evidence of cross-sectionally strong mixing, although every country's environmental policy setting and energy consumption is, in principle, independent. We explain the correlation between the countries as the neighbourhood effects. (see Tanguay et al. [2004])[3] We correct for the cross-sectional dependence following Hoechle [2007]. To test the sensitivity of the choice of treatment and control groups, we follow Dynarski [2004]'s approach. We then compare the results under three classic methods. We find the treatment effects of carbon pricing instruments are statistically significant. The coefficients of interest in the regressions exhibit the 95% confidence intervals away from zero with small p-values. Although the results differ depending on the choice of covariates, we suggest that carbon taxation has preformed well in the past 35 years. They efficiently control CO2 emissions. We also find the evidence that the longer duration a country uses carbon taxation, the greater the reduction in CO2 emissions. We provide evidence to confirm the significant effectiveness of carbon pricing instruments for both a carbon tax and an ETS. For the countries that use both instruments, we find an even more efficient CO2 emission reduction process.

With the signing of the Paris Agreement on CO2 reductions by most countries in December 2015, the results of this study will have considerable implications for policymakers in the years ahead as they find ways to implement the commitments made to emission reductions. Indeed, the findings of this research have clear implications for countries that made commitments to cut their CO2 emissions; that is the use of market-based instruments such as an ETS and especially carbon taxation are effective mitigation methods.

The rest of the article is organised as follows. In Section, 2 we discuss the setting and underlying assumptions of the model. The Data description is provided in Section 3. We report the regression outputs in Section 4 and provide the robustness check in Section 5. Section 6 concludes the article.

2 Model

We test the efficiency of CO2 reduction through the use of carbon pricing instruments — carbon taxation in particular and its interaction with an ETS. Let N be the total number of countries in our data, N_1 be the number of treatment groups that have implemented the environmental policy during the years 1980-2014 and N_0 be the number of control groups that have not changed the environmental policy. We employ a linear panel data model

[2]3000 bootstrap replicates are performed in our main results. In robustness check, we report the results by using 500, 1000 and 2000 replicates.

[3]Martén (2014) suggests that there would be benefits to neighbouring countries to harmonise their energy policies. See the Wall Street Journal `https://blogs.wsj.com/experts/2014/10/02/neighboring-countries-should-harmonize-energy-policies/`

with time and entity fixed effects. This is expressed as follows:

$$CO2_{it} = \alpha d_{it} + \mathbf{x}'_{it}\beta + \theta_i + \delta_t + \varepsilon_{it} \tag{1}$$

where $CO2_{it}$ represents carbon dioxide emissions per capita per year from fossil fuel use and cement production excluding short-cycle biomass burning (for example, agricultural waste burning) and excluding large-scale biomass burning (for example, forest fires). $CO2_{it}$ is the dependent variable, where i represents country and t represents year; d_{it} is the environmental policy dummy variable whose coefficient α is the object of interest in this study. d_{it} equals one if the environment policy of interest is in effect and zero otherwise; $\mathbf{x}'_{it}$ represents a vector of independent variables with parameter vector β including gross domestic product at purchasing power parity per capita per year, energy intensity[4] and the shares of energy consumption of renewables and non-renewables to the primary energy; θ_i and δ_t are country specific and time specific effects respectively; ε_{it} is the error term under different assumptions.

Assumption 1. *The standard error is assumed to be heteroskedastic and autocorrelated. The panel data are assumed to be cross sectionally (spatically) uncorrelated. There is no temporal variation in the environmental policy dummy variable $\widetilde{d}_{it}$.*

It is an assumption widely used for the case when time T is fixed and the numbers of both the treatment and control group are large. However, the number of countries that implement carbon pricing instruments is small. To deal with the few clusters issue, we follow Cameron et al. [2008, 2012] and Cameron and Miller [2010] and use a sufficient number of bootstrap replicates.

We now take account of general forms of cross-sectional dependence and analyse complex patterns of mutual dependence in the panels.

Assumption 2. *The standard error is assumed to be groupwise heteroskedastic, autocorrelated up to some lag length,[5] and cross-sectional (spatial) and temporal dependent of general forms, i.e., Driscoll and Kraay (1997) standard error.*

We can thus rewrite the model as follows:

$$\widetilde{CO2}_{it} = \alpha \widetilde{d}_{it} + \widetilde{\mathbf{x}}'_{it}\beta + \widetilde{\varepsilon}_{it} \tag{2}$$

where the country-year random effects are not average away. By regressing $\widetilde{CO2}_{it}$ on $\widetilde{d}_{it}$ and $\widetilde{\mathbf{x}}'_{it}$, we can obtain an estimation of α.

We suggest the existence of the neighbourhood effects for policy implementation and

[4]Energy intensity (EI) is calculated as the amount of energy a country needs to generate a unit of gross domestic product (GDP), while energy consumption per capita represents total primary energy consumption divided by the population of the country.

[5]The selection of the lag length of $floor[4(T/100)^{2/9}]$ follows Newey and West (1994).

energy use: countries that are geographically located close by or in the same region seem to have similar environmental policies. Not unexpectedly, a country's policy potentially has an impact on its neighbouring countries. Some groups of countries that are part of trade blocs (for example, EU countries) lend themselves considerably to the neighbourhood effects of government policies, including carbon pricing and sometimes even the selection of nuclear and renewable energy. It stands to reason that neighbouring countries that trade with each other to a greater degree are more likely to harmonise their environmental policies. Besides the EU-ETS which is applied to all EU countries, similar ties apply to APEC and OECD members. Some environmental regulations are applied to all the members. Another cause of such effects is the geographic nature: neighbouring countries might share the similar natural resources and therefore the consumption of energy. The claim of the neighbourhood effects is supported by our data in Table (1). We find the implementation of carbon pricing instruments and the consumption of renewables and non-renewables are more alike regionally. An obvious example are the four Nordic countries. Furthermore, for close neighbouring countries, we often find great similarity pairwise. Examples are Australia and New Zealand, USA and Canada, all of which have similar environmental policies. We therefore correct for cross-sectional dependence because of the neighbourhood effects in environmental policy as well as in energy use.

3 Data description

The variable we are interested is the country specific yearly CO2 emission reduction through the use of carbon pricing instruments. We use the shares of consumption of renewable and non-renewable energy sources as the control covariates[6] as well as commonly used measures such as GDP on PPP and energy intensity. The time series data of CO2 emission totals cross countries is obtained from the Emission Database for Global Atmospheric Research (EDGAR), European Commission's Joint Research Centre (JRC).[7] The country-specific CO2 emission totals exclude short-cycle biomass burning (such as agricultural waste burning) and large-scale biomass burning (such as forest fires). The data of national and subnational carbon pricing instruments is compiled from OECD Economic Surveys,[8] International Carbon Action Partnership (ICAP) and World Bank Group.[9] The

[6] We include energy consumption share to the primary energy instead of energy consumption because of 'bad control' problem. For example, one can argue that carbon tax reduces the consumption of coal, while the reduction of coal consumption also reduces CO2 emission. We test the effect of carbon taxation on the energy consumption by regressing CO2 emission on the yearly consumption of each energy source as well as its share on the primary energy. We find that the direct effect of carbon tax on energy consumption share is much less. The regression outputs are given in the appendix.

[7] See: Trends in global CO2 emissions: 2015 Report by PBL Netherlands Environmental Assessment Agency and the European Commission's Joint Research Centre.

[8] See: OECD Economic Surveys: Poland 2012, Issue 7, Volume 2012.

[9] See: State and Trends of Carbon Pricing 2014 and 2015 by World Bank Group.

annual energy consumption data is from BP Statistical Review of World Energy.[10] The data of annual GDP on PPP and population is extracted from the International Monetary Fund (IMF), OECD[11] and World Bank Group databases. To satisfy the common trend assumption in our difference-in-difference model, we keep only the most developed countries following the IMF's criteria for advanced economies[12], World Bank high-income economies[13] and High-income OECD members[14].

The original dataset includes 207 countries. As of December 2014 the number of countries that implemented either carbon taxation or an ETS was 17 and 37 respectively. Eleven countries used both carbon pricing instruments. They are Canada, Denmark, Finland, France, Republic of Ireland, Japan, Norway, Poland, Sweden, Switzerland and United Kingdom. The carbon pricing instrument users are mostly developed countries. To use a difference-in-difference (DID) model to analyse the effect of carbon pricing policies on CO2 emission, we need to choose the closest matched countries. For this reason, we check each country's yearly CO2 emission, GDP preformance and energy intensity growth and drop the developing and the least developed countries.

We then test the consumption of non-renewable energies (including coal, hydroelectricity, natural gas, nuclear and oil) and renewable energies (including solar, wind, geothermal, biomass and other) in each individual country. We drop the consumption of oil due to multicollinearity. It finally leaves us a panel data across 26 representative countries over the time period 1980-2014. In terms of carbon taxation, the number of the treatment group is 11 representing 17 countries who are the real carbon taxation users as of December 2014. Ten out of these eleven countries have implemented both a carbon taxation and an ETS.

A brief summary of the 35-year panel data across 26 countries in 4 regions (grouped by geographic location) is shown in Table (1): Asia Pacific (7), Europe (16), Middle East (1) and North America (2). It summaries the starting date of the policies that were implemented and their length. Note that an interruption in the continuous use of some energy exists. That is, during the 35-year period, some countries may have stopped using some types of energy and switched to others, for example, for the sake of seeking a more efficient solution of CO2 reduction. Such interruption does not apply to the continuous implementation of carbon pricing instruments. Table (1) includes carbon pricing instruments, renewable energies and nuclear energy consumption in use from 1980 to 2014 which are all widely considered as 'environmental friendly' approaches to reduce CO2 efficiently.

[10]See: Statistical Review of World Energy 2015 and 2016 by BP.
[11]See: World Economic and Financial Surveys by IMF and Economic Surveys by OECD.
[12]See: IMF Advanced Economies List. World Economic Outlook, April 2016, p. 148
[13]See: Country and Lending Groups by World Bank Group. Accessed on August 1, 2016
[14]See: Members and partners by OECD. Retrieved 1 August 2016

Table 1: Starting year and length of the use of carbon pricing instruments and energies of interest as of December 2014[a]

Region (6)	Country	ETS	Carbon Tax	Renewables[b]			Nuclear
				Geothermal, Biomass and Other	Solar	Wind	
Asia Pacific (7)	Australia		2012,3[c]	1980,35	1991,24	1993,22	
	Hong Kong SAR, China			2010,5	2010,5	2006,9	
	Japan	2010,5	2012,3	1980,35	1990,25	1993,22	1980,34
	New Zealand	2008,7		1980,35	2007,8	1992,23	
	Korea, Republic of			1995,20	1991,24	1994,21	1980,35
	Singapore			1986,29	2009,6		
	Taiwan, Province of China			1982,33	2000,15	2000,15	
Europe (16)	Austria	2005,10		1980,35	1993,22	1995,20	
	Belgium	2005,10		1980,35	2004,11	1987,28	1980,35
	Denmark	2005,10	1992,23	1983,32	1996,19	1980,35	
	Finland	2005,10	1990,25	1990,25	1991,24	1992,23	1980,35
	France	2005,10	2014,1	1980,35	1992,23	1990,25	1980,35
	Germany	2005,10		1980,35	1990,25	1986,29	1980,35
	Greece	2005,10		1992,19	2004,11	1987,28	
	Ireland, Republic of	2005,10	2010,5	1996,19	2009,6	1992,23	
	Italy	2005,10		1980,35	1989,26	1989,26	1980,8
	Netherlands	2005,10		1980,35	1992,23	1986,29	1980,35
	Norway	2005,10	1991,24	1985,30	2010,5	1999,16	
	Portugal	2005,10		1980,35	1989,20	1989,26	
	Spain	2005,10		1980,35	1989,26	1990,26	1980,35
	Sweden	2005,10	1991,24	1980,35	1993,22	1983,32	1980,35
	Switzerland	2008,7	2008,7[d]	1980,35	1990,25	1996,19	1980,35
	United Kingdom	2005,10	2013,2	1990,25	1984,20	1989,26	1980,35
Middle East (1)	Israel			2008,7	2009,6	2001,14	
North America (2)	Canada	2007,8	2008,7	1980,35	1992,23	1985,30	1980,35
	United States of America	2009,6		1980,35	1983,32	1983,32	1980,35

[a] Source: authors own compilation from OECD Economic Surveys, International Carbon Action Partnership (ICAP), World Bank Group and BP Statistical Review of World Energy.
[b] The consumption of renewable energy includes solar, wind, geothermal, biomass and other waste.
[c] The statistics in each cell show as "the starting year of usage" and "the length of use in the period of 1980-2014". Carbon pricing instruments, renewable or nuclear energy shall be used for more than one day in each year. Blank cells means no record for using by December 2014.
[d] The Swiss ETS started with a five-year voluntary phase as an alternative option to the CO2 levy on fossil fuels in 2008. From 2013, companies who participant in the ETS are exempt from carbon tax. Source: Swiss ETS - International Carbon Action Partnership

As briefly mentioned earlier, we find that countries that are located closely are more likely to design similar environmental policies (and energy use). By the same token, the environmental policies (and energy use) in countries further apart are less alike.

3.1 Subnational jurisdiction

Many subnational jurisdictions have implemented carbon pricing policies such as Québec, California and Tokyo. For our analysis, we use country level data. If subnational carbon pricing instruments (ETS and/or carbon tax) are implemented, for simplicity of model, we consider the instruments to be national. For example, due to the implementation of Alberta SGER (2007 - now), British Columbia carbon tax (2008 - now) and Québec CaT (2013 - now), we consider Canada, as an entity in our model, a country using both carbon taxes and Emissions Trading System. This rule applies to three countries as shown in Table (2): Canada, USA and Japan. The only excluded country is China which started to use a city-level Pilot ETS since 2013.

Table 2: Subnational carbon pricing instruments in operation

Country	Carbon Pricing Instruments	
	ETS	Carbon Tax
Canada	Alberta SGER (2007 - now)	British Columbia carbon tax (2008 - now)
	Québec CaT (2013 - now)	
USA	RGGI (2009 - now)	
	California CaT (2012 - now)	
Japan	Tokyo CaT (2010 - now)	National (2012 - now)
	Saitama ETS (2011 - now)	
	Kyoto ETS (2011 - now)	

Source: World Bank Group, State and Trends of Carbon Pricing, 2015

3.2 Trend of CO2 and GDP preformance

From the Stata graphs, countries show a very similar trend of yearly CO2 emission per capita. Moreover, the common trend of neighbouring countries such as Australia and New Zealand; EU countries including UK (almost all of them are X sharped), Hong Kong and Singapore; Canada and USA; Japan, Taiwan, Korea are clearer. The exemption of our pairwise/region comparison is Greece — because of the severe economic recession it is facing in the recent years. As CO2 emissions are closely correlated with GDP growth, some can argue that Greece's CO2 reduction is from its sharp GDP reduction rather than environmental policies. However, before its recession, the common trend of CO2 emission can still be found.

We first look at the GDP performance and CO_2 emission trend of non-EU countries 1980-2014 from Figure (1).

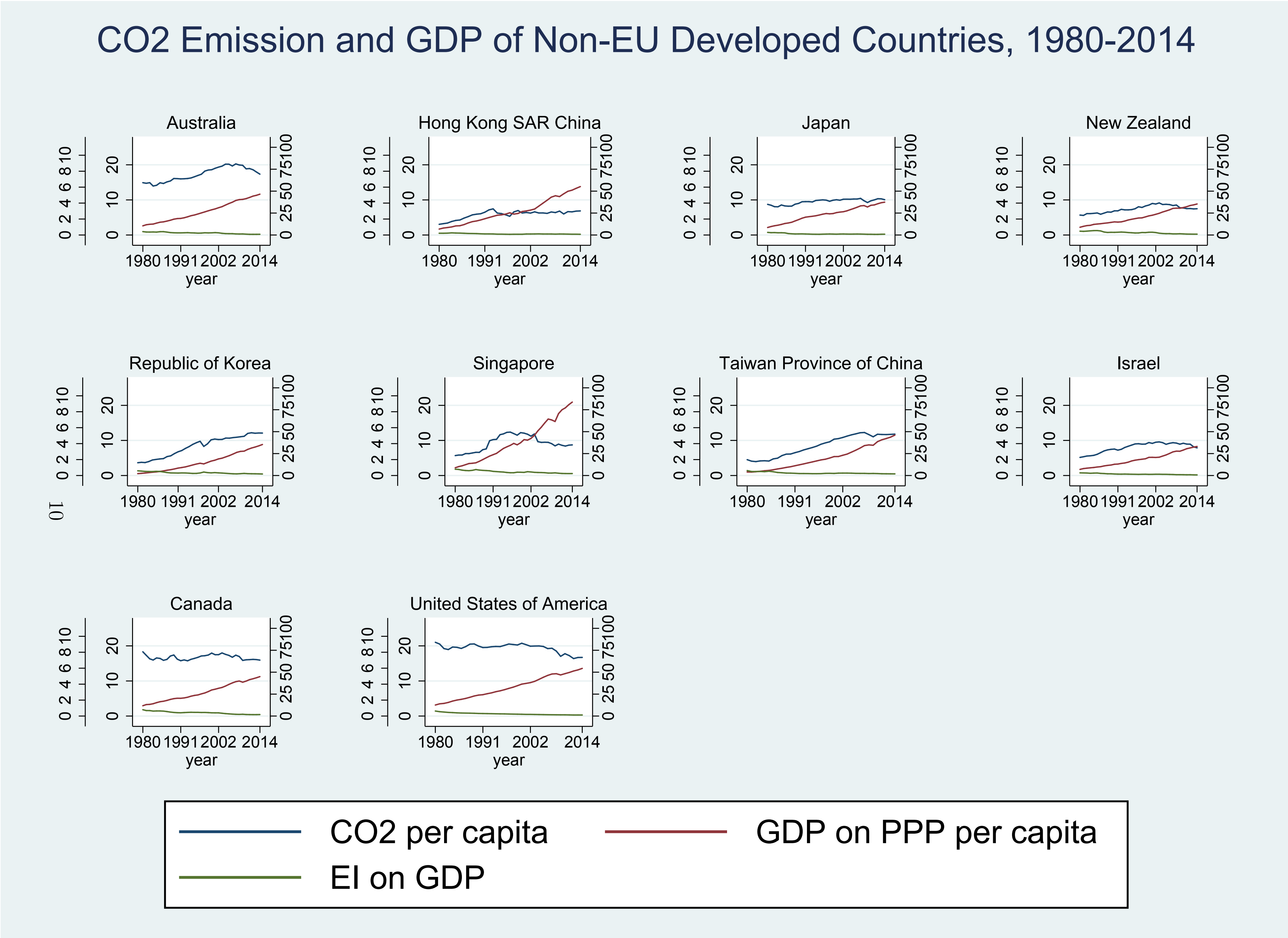

CO2 Emission and GDP of Non-EU Developed Countries, 1980-2014
Australia
Hong Kong SAR China
Japan
New Zealand
Republic of Korea
Singapore
Taiwan Province of China
Israel
Canada
United States of America
year
CO2 per capita
GDP on PPP per capita
EI on GDP

Figure 1:

Ten non-EU countries are all APEC countries except Israel. Australia started to use a carbon tax since 2012 but ended the policy just 3 years later in 2015.[15] New Zealand started to use an ETS from 2008. We can see a clear trend that after the policy implementation in both countries, CO2 emissions showed a gradual reduction. This is due, in no small measure, to the carbon pricing instruments used. Canada is one of the countries that use both carbon pricing instruments — starting tax from 2007 and ETS from 2008. The USA (California) started using an ETS from 2009. Both Canada and the USA have only implemented carbon pricing subnationally. In both countries, CO2 emissions were reduced marginally. The countries with the least impressive records were Korea and Taiwan. Both countries are non-carbon pricing instruments users. Interestingly, Korea started to use nuclear power since 1980 and renewables since 1991. Taiwan has been a renewable energy user since 1982. While Taiwan shows a slight reduction, Korea shows absolutely no reduction. Of course, taking account of GDP preformance, these two countries at least have some control on CO2 emissions.

[15] Our analysis on the tax effect on Australia's CO2 reduction was only based on the data from 1980-2014. We have not estimated the effect of the repeal of the carbon tax on Australia's CO2 reductions.

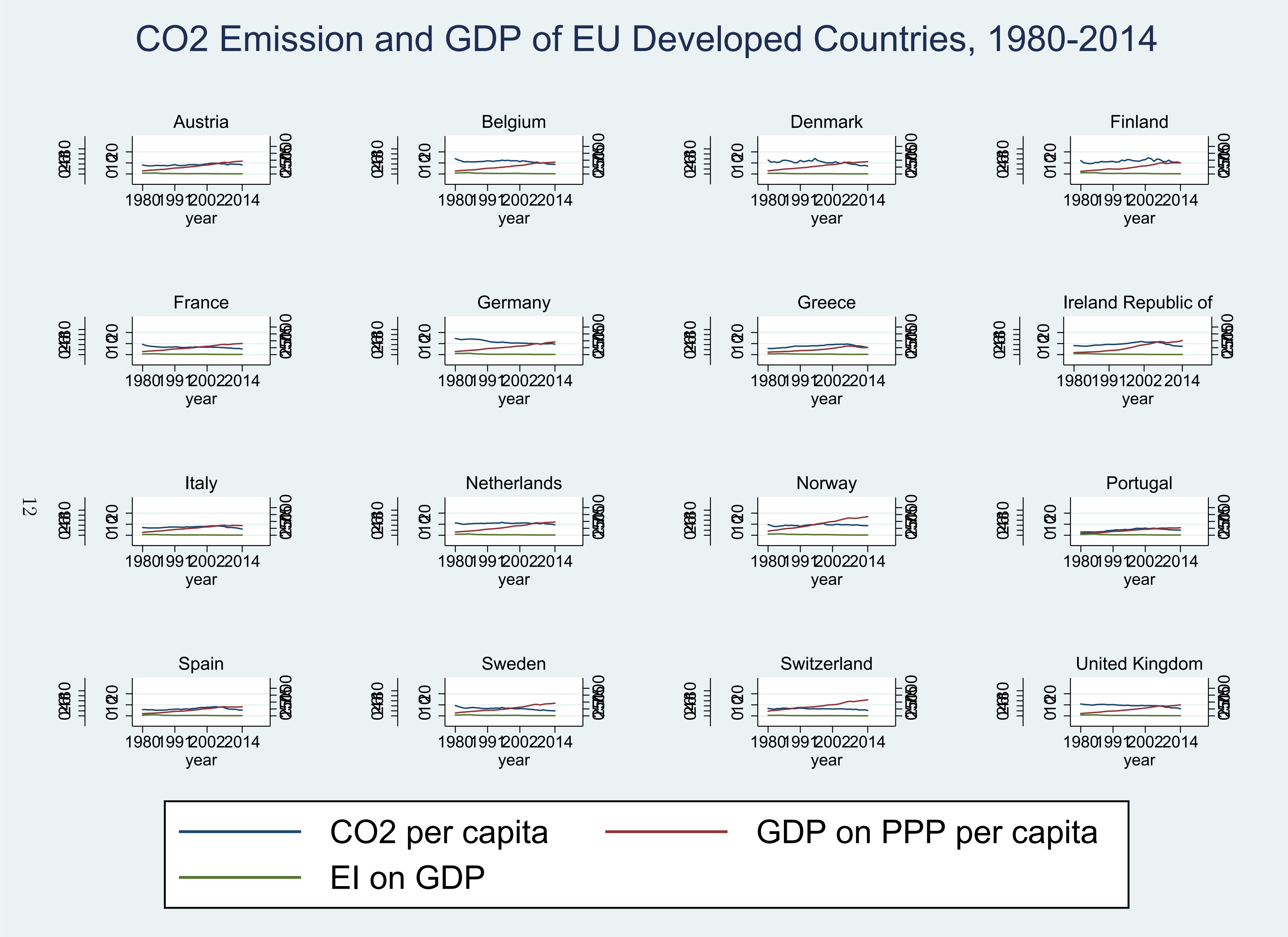
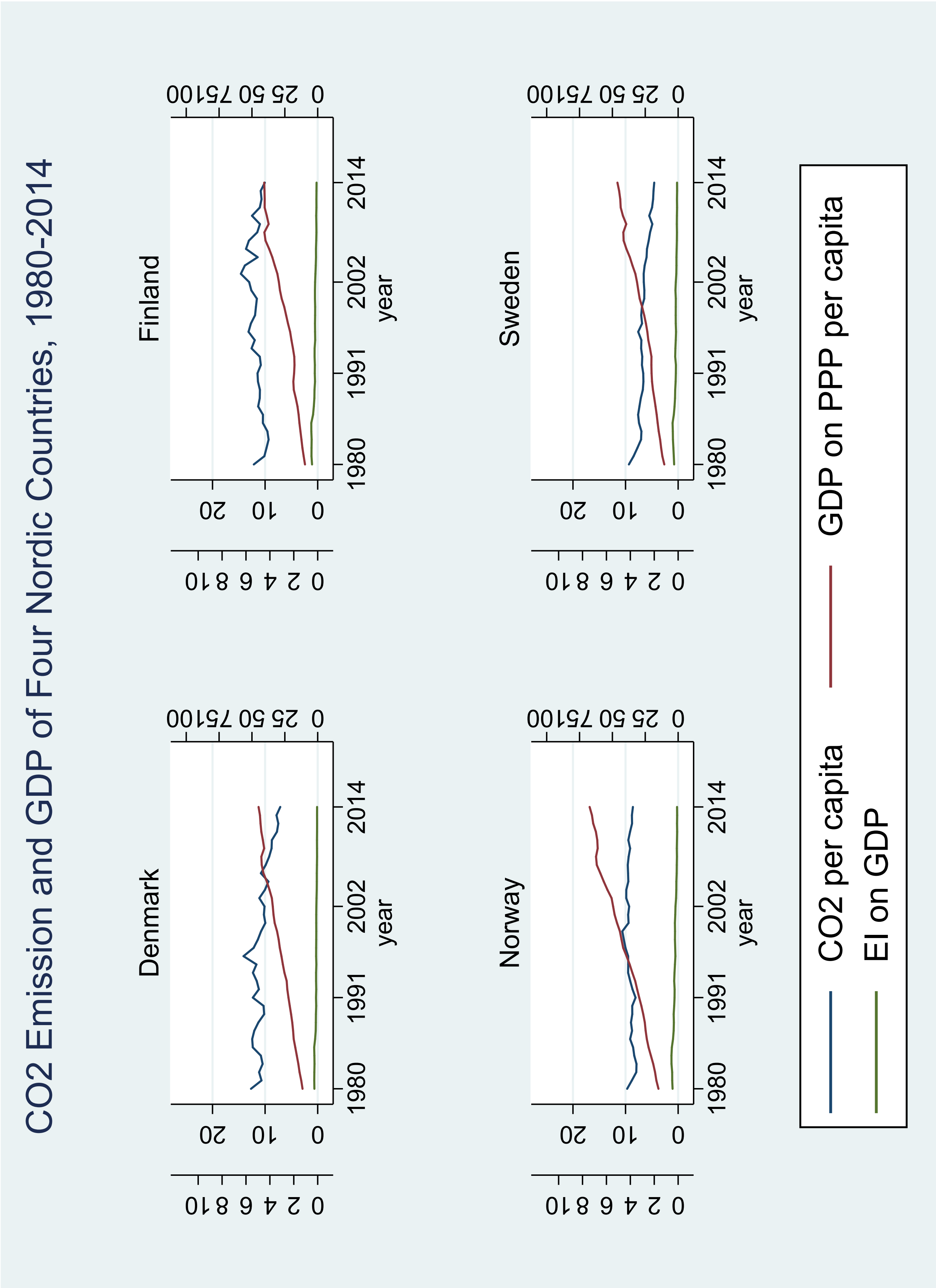

CO2 Emission and GDP of EU Developed Countries, 1980-2014
Austria
Belgium
Denmark
Finland
France
Germany
Greece
Ireland Republic of
Italy
Netherlands
Norway
Portugal
Spain
Sweden
Switzerland
United Kingdom
year
CO2 per capita
GDP on PPP per capita
EI on GDP

Figure 2:

We discuss EU countries separately for a good reason. The EU countries are very similar in many ways; under EU regulation, they have to adapt an ETS. The countries nearby are more alike in terms of renewable energy consumption and advanced 'environmentally friendly' technology development. They also react similarly to the economic shocks. All the 15 EU countries (including UK) in our data have implemented ETS since 2005 without interruption. Switzerland started later in 2008. Besides the four Nordic countries, Ireland (since 2010) and Switzerland (since 2008) have introduced carbon taxation for a considerably long period of time. Carbon Taxation has been implemented in the UK and France for a short period, since 2013 and 2014, respectively. All the EU countries exhibited similar shaped graphs, except Greece since 2008, probably resulting from its GDP recession. Considering each countries' GDP growth, all of them have efficiently controlled CO2 emissions with the use of a carbon pricing mechanism and/or the consumption of renewables and nuclear power.

Figure (3) reports the CO2 emission reduction and GDP preference of four Nordic countries — Sweden, Norway, Finland and Denmark. The four Nordic countries are the first carbon taxation-users, all start from the early nineteen-nineties, and then implement the EU-ETS in the year 2005 which makes them the first ones to use an ETS in the world as well. Following the Paris Agreement, they made commitments to implement deeper than usual emission cuts.



CO2 Emission and GDP of Four Nordic Countries, 1980-2014
Denmark
Finland
Norway
Sweden
year
1980
1991
2002
2014
0 2 4 6 8 10
0 10 20
0 25 50 75 100
CO2 per capita
GDP on PPP per capita
EI on GDP

Figure 3:

From the above figures, we can conclude that CO2 emissions do not necessarily always increase with GDP. Some countries have performed extremely well while maintaining GDP growth, for example, Singapore, Hong Kong, USA and most of the EU countries.

4 Empirical results

4.1 Carbon taxation effects

We first consider a regression model with year and country fixed effects as in Equation (1). We start from including only the carbon taxation dummy to the regression. Then we slowly add more covariates. The regression outputs are reported in Columns (A)-(E) in Table (3). Three methods are used. The usual one-way cluster by country follows Assumption (1), i.e., the standard errors are assumed to be heteroscedastic and autocorrelated. The results are shown in the row of Standard cluster by country. To deal with few clusters problem, still following Assumption (1), we use the wild bootstrap method following Cameron et al. [2008, 2012]. The number of bootstrap replicates is 3000 for each regression.[16] The results are reported in the row of CGM. When the standard errors are robust to very general forms of cross-sectional ('spatial') and temporal dependence, i.e., following Assumption (2), we follow Hoechle [2007] and the results are shown in the row of Hoechle. We find clear evidence that the implementation of carbon taxation efficiently reduces CO2 emissions in the 35-year period.

To estimate the effect of implementation of carbon taxation on CO2 emission per capita per year, we start from a linear regression including only one carbon tax dummy. The estimation equation is as follows:

$$CO2_{it} = \alpha \cdot Tax_{it} + \theta_i + \delta_t + \varepsilon_{it} \tag{3}$$

where the binary regressor Tax_{it} equals one if carbon taxation is in effect in country i in year t and equals zero otherwise. We follow Dynarski [2004], Cameron et al. [2008, 2012] and Hoechle [2007] and compare the regression output. The results are reported in Colomn (A). Countries using carbon taxation reduce their CO2 emissions by -1.007 Million ton per year per capita. The 95% confidence intervals are given in the rows. An interval of -2.166 and 0.153 is obtained with standard cluster by countries. When bootstrapping 3000 replicates, a narrower interval of -2.003 and 0.051 is obtained. In the third row, the standard errors are robust to heteroskedasticity, autocorrelation and cross-sectional (spatial) and temporal dependence. The carbon taxation treatment effect becomes highly

[16]We report the estimates with 500, 1000 and 2000 bootstrap replicates in the section of Robustness Check.

Table 3: Estimates for the effect of carbon taxation on CO2 emission per capita per year

VARIABLES	REGRESSIONS (A)	(B)	(C)	(D)	(E)
Carbon tax	-1.007	-1.105	-0.783	-0.553	-0.605
Energy Intensity[a]		-15.346	-15.829	-15.855	-10.405
GDP on PPP per capita		-0.015	-0.072	-0.091	-0.044
ETS				-1.678	-1.251
Renewables[b]					
Share of geothermal, biomass and other			-26.696	-19.942	-18.909
Share of solar			-60.017	-54.087	-34.599
Share of wind			-23.164	-17.097	-9.891
Non-renewables					
Share of nuclear			-18.036	-17.585	-12.777
Share of hydroelectricity					-13.828
Share of coal					6.803
Share of natural gas					2.710
Country fixed effect	yes	yes	yes	yes	yes
Year fixed effect	yes	yes	yes	yes	yes
95% confidence intervals for carbon taxation effect					
Standard cluster by country	(-2.166 - 0.153)	(-2.187 - -0.023)	(-1.543 - -0.023)	(-1.207 - 0.101)	(-1.206 - -0.004)
CGM (bootstrap reps 3000[c])	(-2.003 - 0.051)	(-2.033 - -0.135)	(-1.595 - 0.029)	(-1.191 - 0.084)	(-1.145 - -0.065)
Hoechle	(-1.518 - -0.495)	(-1.723 - -0.488)	(-1.122 - -0.444)	(-0.991 - -0.218)	(-0.882 - -0.225)
Sample size					
Number of countries	26	26	26	26	26
Observations	910	910	910	910	910
R-squared	0.896	0.900	0.921	0.929	0.937

[a] energy intensity = Primary energy consumption per capita / GDP, where primary energy includes both renewables and non-renewables.
[b] Share of energy consumption = energy consumption / Primary energy consumption.
[c] We apply a country-specific bootstrap.

sufficient — an interval of -1.518 and -0.495 is obtained.

Renewable and nuclear energies are widely considered to be efficient in CO2 emission reduction. Therefore we add them in Regression (C) as control covirates. For countries that use these energies and carbon taxation, an average CO2 reduction of -0.783 is found.

We now slowly add more control covariates as reported in Columns (B)-(E). Although the results differ depending on the choice of covirates, overall, the interval estimates indicate significant treatment effect. In Column (E), Emission Trading Scheme dummy, shares of renewable and non-renewable energy consumption (less oil consumption), GDP on PPP per capita and Enengy Intensity of GDP are the control covariates. The regression now becomes:

$$\begin{aligned} CO2_{it} &= \alpha Tax_{it} + \beta_1 EI_{it} + \beta_2 GDPonPPP_{it} + \beta_3 ETS_{it} + \beta_4 ShareGeothermalBiomass_{it} \\ &\quad + \beta_5 ShareSolar_{it} + \beta_6 ShareWind_{it} + \beta_7 ShareNuclear_{it} + \beta_8 ShareCoal_{it} \\ &\quad + \beta_9 ShareHydroelectricity_{it} + \beta_{10} ShareNaturalGas_{it} + \theta_i + \delta_t + \varepsilon_{it} \end{aligned} \tag{4}$$

On average, the implementation of carbon taxation reduces CO2 by -0.605 Million ton per capita per year. Using the standard cluster by country, the confidence interval is $(-1.206 - -0.004)$. The interval changes to $(-1.145 - -0.065)$ when we apply the country specific bootstrap. When correcting for cross-sectional dependence, the confidence interval of $(-0.882 - -0.225)$ is narrower.

Next, we examine whether the length of use of carbon taxation has an effect on CO2 emissions. We create new variables for every 5 more years of carbon taxation implementation as shown in Table (4). In Regression (A), we exclude any control covirates. The estimates are not statistically significant. The results improves when we control for ETS dummy, energy intensity and GDP on PPP per capita as shown in Regression (B). We observe a clear decreasing trend — a CO2 reduction of -0.655 Million ton per capita in the first five years and -2.382 for a over 20-year taxation implementation. Finally, we add the shares of renewable and non-renewable energy consumption (less oil consumption) in Regression (C). The results are highly significant as the robust confidence intervals show. In the first 5-year of using carbon taxation, countries in the treatment group reduce CO2 by -0.632 Million ton per capita. The longer the duration of carbon taxation implementation, the more CO2 emissions are reduced. For the four countries that have been using carbon taxation for over 20 years: Denmark, Finland, Norway and Sweden, the CO2 reduction increased to -1.757 Million ton per capita as reported in the row of tax21to25.

Table 4: Estimates for the effect of carbon taxation on CO2 emission per capita per year

	REGRESSIONS								
	(A)			(B)			(C)		
VARIABLES	Std cluster by cty	CGM	Hoechle	Std cluster by cty	CGM	Hoechle	Std cluster by cty	CGM	Hoechle
tax1to5	-0.348	-0.348	-0.348	-0.655	-0.655	-0.655***	-0.632**	-0.632**	-0.632***
	(-0.991 - 0.296)	(-0.992 - 0.297)	(-0.971 - 0.276)	(-1.458 - 0.147)	(-1.476 - 0.165)	(-1.106 - -0.205)	(-1.141 - -0.122)	(-1.148 - -0.115)	(-0.965 - -0.298)
tax6to10	0.014	0.014	0.014	-0.810	-0.810	-0.810**	-0.746**	-0.746**	-0.746***
	(-0.943 - 0.970)	(-0.732 - 0.760)	(-0.695 - 0.723)	(-1.850 - 0.229)	(-1.994 - 0.373)	(-1.437 - -0.184)	(-1.428 - -0.065)	(-1.468 - -0.025)	(-1.216 - -0.277)
tax11to15	0.020	0.020	0.020	-1.133	-1.133	-1.133***	-1.146**	-1.146**	-1.146***
	(-1.526 - 1.566)	(-0.644 - 0.685)	(-0.566 - 0.606)	(-2.771 - 0.506)	(-3.002 - 0.737)	(-1.776 - -0.489)	(-2.166 - -0.126)	(-2.269 - -0.024)	(-1.741 - -0.552)
tax16to20	-0.862	-0.862	-0.862*	-1.368	-1.368	-1.368***	-1.305**	-1.305**	-1.305***
	(-2.642 - 0.918)	(-2.754 - 1.030)	(-1.728 - 0.004)	(-3.176 - 0.439)	(-3.465 - 0.729)	(-2.181 - -0.556)	(-2.421 - -0.190)	(-2.521 - -0.090)	(-1.941 - -0.670)
tax21to25	-1.663*	-1.663	-1.663***	-2.382**	-2.382*	-2.382***	-1.757***	-1.757***	-1.757***
	(-3.489 - 0.164)	(-3.831 - 0.505)	(-2.496 - -0.829)	(-4.291 - -0.472)	(-4.921 - 0.158)	(-3.508 - -1.255)	(-2.929 - -0.585)	(-3.067 - -0.446)	(-2.644 - -0.869)
ETS				-1.495***	-1.495**	-1.495***	-1.074**	-1.074**	-1.074***
				(-2.588 - -0.401)	(-2.747 - -0.243)	(-2.204 - -0.785)	(-1.990 - -0.157)	(-2.095 - -0.053)	(-1.718 - -0.429)
energy intensity				-14.082*	-14.082*	-14.082***	-7.139	-7.139	-7.139
				(-29.605 - 1.441)	(-29.569 - 1.405)	(-23.297 - -4.867)	(-19.790 - 5.511)	(-18.821 - 4.543)	(-16.047 - 1.769)
GDP on PPP p.c.				0.051	0.051	0.051***	0.042	0.042	0.042***
				(-0.024 - 0.126)	(-0.029 - 0.130)	(0.031 - 0.071)	(-0.021 - 0.105)	(-0.031 - 0.115)	(0.019 - 0.064)
Shares of energy[c]									
share hydro							-19.794***	-19.794***	-19.794***
							(-29.816 - -9.772)	(-34.409 - -5.179)	(-24.283 - -15.305)
share coal							7.485***	7.485***	7.485***
							(2.064 - 12.906)	(2.394 - 12.576)	(5.583 - 9.388)
share natgas							7.434**	7.434**	7.434***
							(0.685 - 14.183)	(0.589 - 14.280)	(5.328 - 9.541)
share geoth							-0.079	-0.079	-0.079
							(-20.566 - 20.409)	(-2.560e+19 - 2.560e+19)	(-6.082 - 5.925)
share solar							-41.089***	-41.089***	-41.089***
							(-70.035 - -12.142)	(-64.702 - -17.476)	(-68.132 - -14.046)
share wind							-11.301	-11.301	-11.301***
							(-26.134 - 3.531)	(-27.528 - 4.926)	(-17.270 - -5.332)
share nuclear							-9.023**	-9.023***	-9.023***
							(-17.840 - -0.205)	(-14.901 - -3.144)	(-13.275 - -4.770)
Country fixed effect		yes			yes			yes	
Sample size									
Number of countries		26			26			26	
Observations		910			910			910	
R-squared		0.864			0.898			0.926	

[a] Robust confidence interval in parentheses. *** p<0.01, ** p<0.05, * p<0.1
[b] CGM Bootstrap reps 3000.
[c] The covariates 'Shares of energy' represent the shares of all renewable and non-renewable energy consumption less oil.

In the robustness check we test the model with a different selection of control group. Following Dynarski [2004], we drop the non-carbon tax users which leave us date of 11 countries. These countries are in the control group before carbon taxes are implemented. Their identities change to the treatments once carbon taxes are introduced. We find that our main results are not sensitive to the choice of the control group. Therefore, we suggest a clear evidence on the effectiveness of the implementation of carbon taxation on CO2 emissions reduction.

4.2 The interaction of carbon taxation and ETS

Next, we test the joint effect of carbon taxation and ETS. We try to answer whether the use of both carbon pricing instruments would reduce CO2. By comparing the regression outputs we get above, we try to determine whether a combination of both instruments are a more efficient way to reduce CO2 emissions. The regression is as follows:

$$CO2_{it} = \alpha(Tax * ETS)_{it} + \mathbf{x'}_{it}\beta + \theta_i + \delta_t + \varepsilon_{it} \tag{5}$$

where the environmental policy of interest becomes the interaction of carbon taxation and an ETS. $(Tax*ETS)_{it}$ equals one if country i used both carbon pricing instruments in year t and equals zero otherwise. Ten countries in the treatment group are Japan, Denmark, Finland, France, Ireland, Norway, Sweden, Switzerland, United Kingdom and Canada.

The results are reported in Table (5). We start from regressing CO2 per year per capita on the $Tax*ETS$ dummy only as in Column (A). A yearly reduction of -1.248 Million ton is found for the countries who use both carbon taxation and ETS. From the 95% confidence intervals reported in the parentheses, the results are statistically significant. The coefficient changes to -1.348 when we control for the Energy Intensity and GDP on PPP per capita to the regression as Column (B) shows. In Regression (C), we add the renewable and nuclear energies as control covirates. For countries that use these energies and both carbon pricing instruments, an average CO2 reduction of -1.057 is found. In Column (D), we report the regression including all shares of renewables and non-renewables consumption. The implementation of both instruments effectively reduces -0.886 Million ton CO2 per capita per year. As before, to correct the standard error estimates, three methods are used. At the 95% confidence level, the results are statistically significant.

Furthermore, we compare the treatment effects of tax-only (Table 3) and a joint use of both carbon pricing instruments. We find that a joint use performs better: more CO2 emission has been reduced.

Next, we examine whether the length of the use of both instruments has an effect on CO2 reduction. We create new variables for every three additional years of implementation. The

Table 5: Estimates for the effect of carbon pricing instruments on CO2 emission per capita per year

	REGRESSIONS			
VARIABLES	(A)	(B)	(C)	(D)
Tax X ETS[a]	-1.248	-1.348	-1.057	-0.886
Energy Intensity		-15.363	-15.723	-9.863
GDP on PPP per capita		-0.015	-0.072	-0.025
Renewables				
Share of geothermal, biomass and other			-25.710	-22.508
Share of solar			-70.268	-45.387
Share of wind			-22.144	-12.341
Non-renewables				
Share of nuclear			-18.035	-11.817
Share of hydroelectricity				-12.920
Share of coal				8.214
Share of natural gas				3.824
Country fixed effect	yes	yes	yes	yes
Year fixed effect	yes	yes	yes	yes
95% confidence intervals for carbon taxation effect				
Standard cluster by country	(-2.449 - -0.047)	(-2.529 - -0.167)	(-1.876 - -0.239)	(-1.616 - -0.156)
CGM (bootstrap reps 3000)	(-2.431 - -0.065)	(-2.585 - -0.111)	(-1.933 - -0.182)	(-1.683 - -0.089)
Hoechle	(-1.713 - -0.783)	(-1.871 - -0.825)	(-1.517 - -0.597)	(-1.271 - -0.502)
Sample size				
Number of countries	26	26	26	26
Observations	910	910	910	910
R-squared	0.897	0.901	0.922	0.934

[a] It is to test the effect of the interaction of ETS and carbon tax on CO2 emission. 1 for the countries who use both ETS and carbon tax, 0 otherwise.

results are reported in Table (6). We first exclude any control covirates as Regression (A) shows. The treatment effect is immediate: the yearly emission reduction of -0.572 Million ton is found in the first three-year period. For a country that has used both instruments for 10 years, the emission reduction of -2.248 is dramatic. By including Energy Intensity and GDP on PPP per capita in Regression (B), the results improves sightly. We finally control for the shares of energy consumption as shown in Regression (C). Starting from an immediate reduction of -1.078 in the first three-year period, approximately 0.1 Million ton more CO2 emission reduces for every three more years of implementation. We therefore see clear evidence of a stable decreasing trend: the longer the duration of the implementation, the more CO2 emission reduces. From the 95% of confidence interval in parentheses, the results are highly significant.

Table 6: Estimates for the effect of carbon pricing instruments on CO2 emission per capita per year

	REGRESSIONS								
	(A)			(B)			(C)		
VARIABLES	Std cluster by cty	CGM	Hoechle	Std cluster by cty	CGM	Hoechle	Std cluster by cty	CGM	Hoechle
taxXets1to3	-0.572	-0.572	-0.572***	-1.328**	-1.328**	-1.328***	-1.078***	-1.078***	-1.078***
	(-1.300 - 0.156)	(-1.324 - 0.179)	(-0.975 - -0.170)	(-2.409 - -0.247)	(-2.481 - -0.175)	(-1.796 - -0.860)	(-1.778 - -0.378)	(-1.874 - -0.282)	(-1.451 - -0.705)
taxXets4to6	-1.110***	-1.110**	-1.110***	-2.064***	-2.064***	-2.064***	-1.437***	-1.437***	-1.437***
	(-1.872 - -0.348)	(-2.124 - -0.096)	(-1.447 - -0.773)	(-3.240 - -0.888)	(-3.467 - -0.660)	(-2.713 - -1.414)	(-2.202 - -0.672)	(-2.313 - -0.561)	(-1.890 - -0.983)
taxXets7to9	-1.696***	-1.696*	-1.696***	-2.752***	-2.752***	-2.752***	-1.500***	-1.500***	-1.500***
	(-2.846 - -0.546)	(-3.595 - 0.203)	(-1.994 - -1.398)	(-4.111 - -1.393)	(-4.545 - -0.959)	(-3.405 - -2.099)	(-2.324 - -0.675)	(-2.414 - -0.585)	(-1.984 - -1.015)
taxXets10plus	-2.248***	-2.248***	-2.248***	-3.399***	-3.399***	-3.399***	-1.545**	-1.545***	-1.545***
	(-3.590 - -0.906)	(-3.540 - -0.956)	(-2.557 - -1.939)	(-4.891 - -1.906)	(-5.352 - -1.445)	(-4.119 - -2.678)	(-2.688 - -0.402)	(-2.631 - -0.459)	(-2.055 - -1.035)
Energy Intensity				-17.619**	-17.619**	-17.619***	-9.137	-9.137	-9.137**
				(-33.535 - -1.703)	(-34.260 - -0.978)	(-24.733 - -10.505)	(-21.987 - 3.713)	(-22.072 - 3.799)	(-16.812 - -1.462)
GDP on PPP per capita				0.020	0.020	0.020*	0.028	0.028	0.028**
				(-0.043 - 0.084)	(-0.043 - 0.084)	(-0.003 - 0.044)	(-0.028 - 0.083)	(-0.032 - 0.088)	(0.005 - 0.051)
Shares of energy									
share hydro							-18.060***	-18.060***	-18.060***
							(-27.609 - -8.511)	(-31.395 - -4.725)	(-21.997 - -14.123)
share coal							8.099***	8.099***	8.099***
							(2.343 - 13.856)	(2.408 - 13.791)	(5.933 - 10.266)
share natgas							7.527**	7.527**	7.527***
							(0.520 - 14.533)	(0.649 - 14.405)	(5.315 - 9.738)
share geoth							-12.088	-12.088	-12.088***
							(-35.490 - 11.314)	(-57.983 - 33.807)	(-17.743 - -6.432)
share solar							-57.239***	-57.239***	-57.239***
							(-89.872 - -24.606)	(-90.133 - -24.345)	(-72.659 - -41.819)
share wind							-15.984**	-15.984*	-15.984***
							(-31.942 - -0.026)	(-32.771 - 0.804)	(-23.775 - -8.193)
share nuclear							-8.749*	-8.749**	-8.749***
							(-18.500 - 1.002)	(-16.270 - -1.228)	(-13.240 - -4.258)
Country fixed effect		yes			yes			yes	
Sample size									
Number of countries		26			26			26	
Observations		910			910			26	
R-squared		0.866			0.888			0.923	

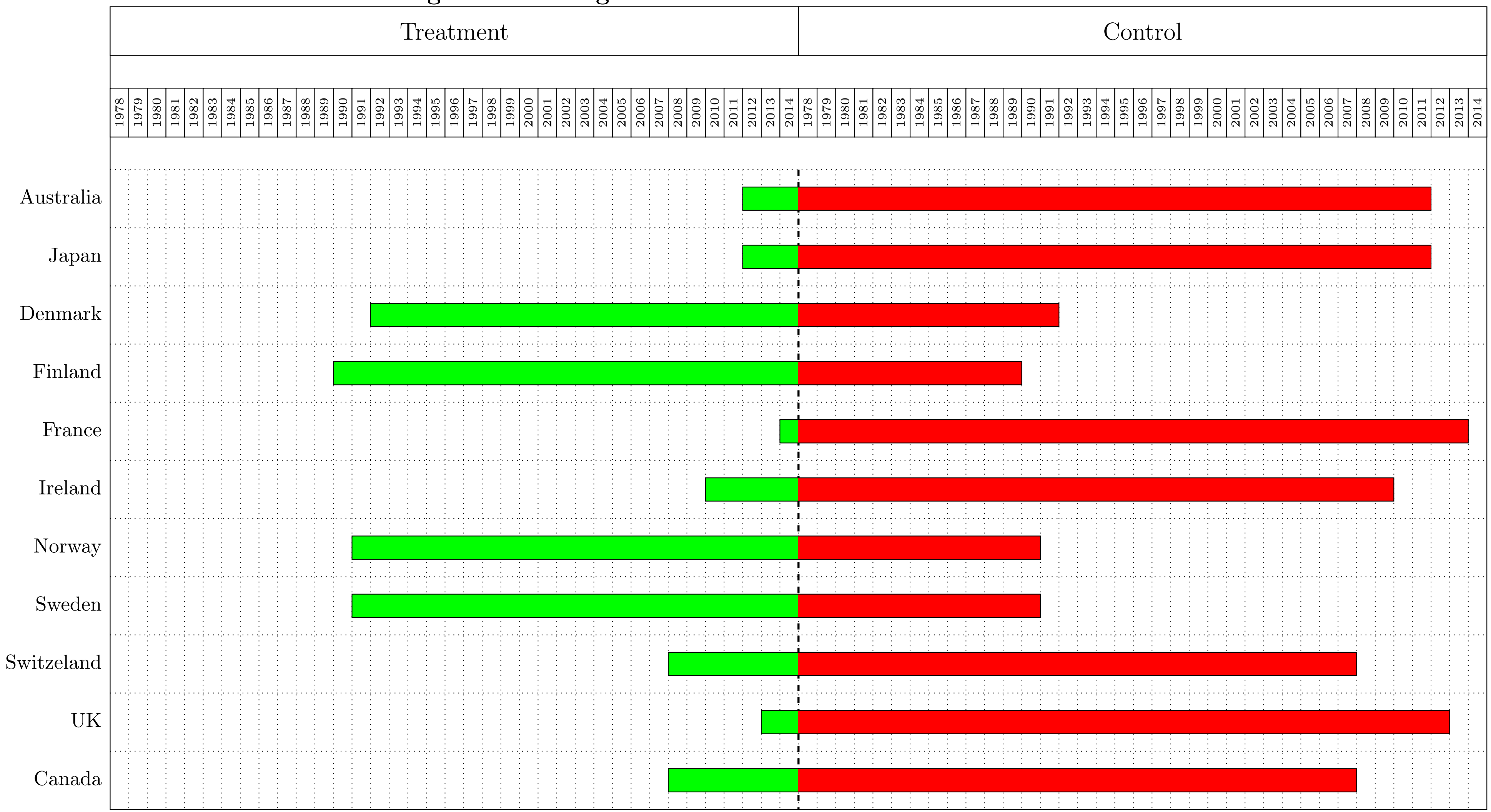
[a] Robust confidence interval in parentheses.
[b] The covariates 'Shares of energy' represent the shares of all renewable and non-renewable energy consumption less oil.

5 Robustness check

5.1 Selection of the control group

We suggest there is little doubt that carbon pricing instruments users have higher incentive to reduce CO2 emissions and contribute more to a cleaner environment. Therefore they might have stronger preferences towards the use of nuclear or renewable energy, compared to the countries that have not implemented either carbon taxation or ETS by 2014. Also taking account of countries' different GDP performance and Energy Intensity improvement as well as some other country specific effects which we do not include in our model (such as nature resource, cars emission and fuel economy figures), we suspect that the non-carbon pricing instrument users form a poor control group. We follow Dynarski [2004] and test the sensitivity of our results to the choice of control group. We drop 15 non-carbon taxation users from the sample and test the effect of carbon taxation from the staggered timing of its implementation across countries. The identification of the treatments (in green) and controls (in red) is illustrated in Figure (4). Finland was the first to introduce carbon tax in 1990. Thus before 1990, all the 11 countries are the controls. In 1990, Finland moves into the treatment group, followed by Norway and Sweden in 1991 and then by Denmark in 1992. France is the last country to join the treatments in our sample. It started to use carbon tax in 2014. Thus by 2014, all the eleven countries are in the treatment group.

Figure 4: Timing of introduction of carbon taxation



The regression output is reported in Table (7). Overall, the estimations are not sensitive to the choice of treatment and control group, although the confidence interval becomes less significant. We compare the results in Column (D) in Table (3) and Column (A) in Table (7), the estimation of treatment effect decreases slightly from -0.605 to -0.689. Similarly, we find the estimations drop by comparing results in Column (C) in Table (4) and Column (B) in Table (7). A 5-year use of carbon taxation reduces CO2 by -0.845 Million ton per capita. For every five more year's use of carbon taxation, we find approximately 0.5 Million per capita less CO2 emission. As these results are similar to the ones we obtained earlier, it becomes clear that the longer duration of use of carbon taxation, the more CO2 reduces. For countries that have been using carbon taxation for more than 20 years, the CO2 reduction of -2.927 demonstrates its effectiveness.

Table 7: Estimates for the effect of carbon taxation on CO2 emission per capita per year, carbon taxation users only

	REGRESSIONS					
	(A)			(B)		
VARIABLES	Std cluster by cty	CGM	Hoechle	Std cluster by cty	CGM	Hoechle
carbon taxation	-0.689*	-0.689	-0.689**			
	(-1.474 - 0.096)	(-1.622 - 0.244)	(-1.369 - -0.009)			
tax1to5				-0.845**	-0.845**	-0.845***
				(-1.483 - -0.208)	(-1.624 - -0.067)	(-1.293 - -0.398)
tax6to10				-1.086**	-1.086*	-1.086***
				(-2.020 - -0.152)	(-2.332 - 0.160)	(-1.557 - -0.615)
tax11to15				-1.676**	-1.676	-1.676***
				(-3.300 - -0.051)	(-3.686 - 0.334)	(-2.272 - -1.079)
tax16to20				-2.174**	-2.174**	-2.174***
				(-3.913 - -0.435)	(-4.144 - -0.204)	(-3.087 - -1.261)
tax21to25				-2.927***	-2.927**	-2.927***
				(-4.947 - -0.907)	(-5.403 - -0.450)	(-4.195 - -1.658)
ETS		yes			yes	
Energy Intensity		yes			yes	
GDP on PPP per capita		yes			yes	
Shares of energy[c]		yes			yes	
Country fixed effect		yes			yes	
Year fixed effect		yes				
Sample size						
Number of countries		11			11	
Observations		385			385	
R-squared		0.967			0.966	

[a] Robust confidence interval in parentheses.
[b] CGM Bootstrap reps 3000.
[c] The covariates 'Shares of energy' represent the shares of all renewable and non-renewable energy consumption less oil.

Next, we test the sensitivity of our results in the joint effect of both carbon pricing instruments to the choice of control group. We include ten countries that have used both carbon taxation and ETS in the 35-year period. From 1980-2004, all countries are controls. In 2005, the four Nordic countries first move into the treatment group. Switzerland and Canada follow in 2008. France is the last to join the treatments in 2014.

We first compare Regression (C) in Table (5) with Regression (A) in Table (8). The estimate of reduction increases slightly from -0.886 to -0.645 million tons per year and the results are less significant given by the wider confidence intervals. From Regression (A) in Table (8), we see a similar decreasing trend as shown in Regression (C) in Table (6). An immediate emission reduction of -0.932 is found in the first three-year period.

Table 8: Estimates for the effect of carbon pricing instruments on CO2 emission per capita per year, carbon pricing instruments users only

	REGRESSIONS					
	(A)			(B)		
VARIABLES	Std cluster by cty	CGM	Hoechle	Std cluster by cty	CGM	Hoechle
Tax X ETS	-0.645	-0.645	-0.645***			
	(-1.442 - 0.152)	(-1.610 - 0.320)	(-1.077 - -0.214)			
taxXets1to3				-0.932**	-0.932**	-0.932***
				(-1.590 - -0.274)	(-1.821 - -0.043)	(-1.247 - -0.617)
taxXets4to6				-1.443***	-1.443**	-1.443***
				(-2.372 - -0.514)	(-2.718 - -0.168)	(-1.910 - -0.976)
taxXets7to9				-1.737***	-1.737**	-1.737***
				(-2.821 - -0.652)	(-3.174 - -0.300)	(-2.290 - -1.183)
taxXets10plus				-1.923***	-1.923**	-1.923***
				(-3.193 - -0.652)	(-3.513 - -0.332)	(-2.619 - -1.226)
Energy Intensity		yes			yes	
GDP on PPP per capita		yes			yes	
Shares of energy[c]		yes			yes	
Country fixed effect		yes			yes	
Year fixed effect		yes				
Sample size						
Number of countries		10			10	
Observations		350			350	
R-squared		0.967			0.960	

[a] Robust confidence interval in parentheses. *** p<0.01, ** p<0.05, * p<0.1
[b] CGM Bootstrap reps 3000.
[c] The covariates 'Shares of energy' represent the shares of all renewable and non-renewable energy consumption less oil.

This figure doubles for the countries that have used both carbon pricing instruments for ten years as reported in the row of taxXets10plus. Although the results change, overall, we find the choice of the treatment and control groups is not very sensitive. We could still suggest a clear evidence that the implementation of both carbon taxation and ETS has efficiently reduced CO2 emission over the past 35 years. And it performs slightly better than a carbon tax-only implementation.

5.2 Selection of bootstrap replicates

Now we examine the results with all 26 countries in our data but less bootstrap replicates. We show that the above findings hold with different selections of replicates. We first estimates the effect of carbon taxation on CO2 emission. The estimates with 500, 1000 and 2000 bootstrap replicates are reported in Table (9) Regressions (A), (C) and (E), respectively. By comparing to the $(-1.145 - -0.065)$ confident interval in Table (3) Regression (E), the confident intervals are wider with less replicates. However, the results are statistically significant at 10% level. We then test the length of the use of carbon taxation. The estimates are reported in Table (9) Regressions (B), (D) and (F). The results coincide with the our findings in Table (4) Regression (C). In spite of the slightly wider confident intervals, the results are statistically significant.

Next, we test the joint effect of carbon taxation and ETS with less bootstrap replicates. The results are reported in Table (10). We compare Regressions (A), (C) and (E) with the confident interval $(-1.683 - -0.089)$ in Table (5) Regression (D). The intervals change

Table 9: Estimates for the effect of carbon taxation on CO2 emission per capita per year with 500, 1000 and 2000 bootstrap replicates

	REGRESSIONS					
	reps 500		reps 1000		reps 2000	
VARIABLES	(A)	(B)	(C)	(D)	(E)	(F)
carbon taxation	-0.605*		-0.605*		-0.605*	
	(-1.245 - 0.035)		(-1.295 - 0.086)		(-1.222 - 0.013)	
tax1to5		-0.632**		-0.632**		-0.632**
		(-1.145 - -0.118)		(-1.172 - -0.091)		(-1.112 - -0.151)
tax6to10		-0.746**		-0.746**		-0.746**
		(-1.428 - -0.064)		(-1.473 - -0.020)		(-1.448 - -0.045)
tax11to15		-1.146*		-1.146*		-1.146**
		(-2.359 - 0.067)		(-2.341 - 0.048)		(-2.277 - -0.015)
tax16to20		-1.305**		-1.305*		-1.305**
		(-2.599 - -0.012)		(-2.633 - 0.022)		(-2.538 - -0.072)
tax21to25		-1.757**		-1.757**		-1.757***
		(-3.185 - -0.328)		(-3.282 - -0.232)		(-3.054 - -0.460)
ETS	yes	yes	yes	yes	yes	yes
Energy Intensity	yes	yes	yes	yes	yes	yes
GDP on PPP p.c.	yes	yes	yes	yes	yes	yes
Shares of energy[c]	yes	yes	yes	yes	yes	yes
Country fixed effect	yes	yes	yes	yes	yes	yes
Year fixed effect	yes		yes		yes	

[a] Robust confidence interval in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$
[b] For all regressions in table, Sample size: Number of countries: 26. Observations: 910.
[c] The covariates 'Shares of energy' represent the shares of all renewable and non-renewable energy consumption less oil.

slightly with 500, 1000 and 2000 replicates, however, the results are statistically significant at 5% confidence level. We also compare Regressions (B), (D) and (F) with the results in Table (6) Regression (C). Note that, with 2000 replicates, the results are statistically significant at 1%. It provides evidence that the longer the carbon pricing instruments are used, the more CO2 emission has been reduced.

Table 10: Estimates for the effect of carbon pricing instruments on CO2 emission per capita per year with 500, 1000 and 2000 bootstrap replicates

	REGRESSIONS					
	reps 500		reps 1000		reps 2000	
VARIABLES	(A)	(B)	(C)	(D)	(E)	(F)
Tax X ETS	-0.886**		-0.886**		-0.886**	
	(-1.633 - -0.140)		(-1.732 - -0.041)		(-1.650 - -0.123)	
taxXets1to3		-1.078**		-1.078**		-1.078***
		(-1.919 - -0.238)		(-1.919 - -0.238)		(-1.886 - -0.270)
taxXets4to6		-1.437***		-1.437***		-1.437***
		(-2.498 - -0.376)		(-2.346 - -0.527)		(-2.346 - -0.527)
taxXets7to9		-1.500***		-1.500***		-1.500***
		(-2.520 - -0.480)		(-2.520 - -0.480)		(-2.391 - -0.608)
taxXets10plus		-1.545***		-1.545**		-1.545***
		(-2.596 - -0.494)		(-2.750 - -0.341)		(-2.667 - -0.423)
ETS	yes	yes	yes	yes	yes	yes
Energy Intensity	yes	yes	yes	yes	yes	yes
GDP on PPP p.c.	yes	yes	yes	yes	yes	yes
Shares of energy[c]	yes	yes	yes	yes	yes	yes
Country fixed effect	yes	yes	yes	yes	yes	yes
Year fixed effect	yes		yes		yes	

[a] Robust confidence interval in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$
[b] For all regressions in table, Sample size: Number of countries: 26. Observations: 910.
[c] The covariates 'Shares of energy' represent the shares of all renewable and non-renewable energy consumption less oil.

Therefore we show that our main findings hold even with different selections of bootstrap replicates. With more replicates, better results are obtained.

6 Conclusion

In this article, we have tested the efficiency of carbon taxation by using evidence across 26 of the most developed countries for the period 1980-2014. We employ a simple difference-in-difference model and correct the standard error following Dynarski [2004], Cameron et al. [2008, 2012] and Hoechle [2007]. The error terms are robust to heteroskedasticity, auto-correlation and cross-sectional dependence. We confirm that in the past 35 years, carbon taxation has effectively reduced CO2 emissions per capita in the developed world. The longer the duration of taxation implementation, the more efficient the reduction of CO2 is found. For countries that have been using both an ETS and carbon taxation, we find the evidence of an even more efficient reduction in CO2 emissions.

The findings of this research have clear implementations for countries that made commitments to cut their CO2 emissions. The use of market-based instruments such as a carbon taxation or a combination with an ETS is an effective mitigation method. Countries around the world will need to give serious consideration to adopting these measures.

An area for further research could be that countries' performance after 2014, especially after Paris Agreement where most countries, developed and developing, become open to voluntarily cutting their emissions. Other areas that could be examined include countries that have been the worst CO2 emitters. We especially wish to provide evidence to these countries that have not yet adopted market-based mechanisms like carbon taxes to mitigate emissions.

References

A. Bruvoll and B. M. Larsen. Greenhouse gas emissions in norway: do carbon taxes work? *Energy policy*, 32(4):493–505, 2004.

A. C. Cameron and D. L. Miller. Robust inference with clustered data. *Handbook of empirical economics and finance*, pages 1–28, 2010.

A. C. Cameron, J. B. Gelbach, and D. L. Miller. Bootstrap-based improvements for inference with clustered errors. *The Review of Economics and Statistics*, 90(3):414–427, 2008.

A. C. Cameron, J. B. Gelbach, and D. L. Miller. Robust inference with multiway clustering. *Journal of Business & Economic Statistics*, 2012.

B. Doda et al. Evidence on co2 emissions and business cycles. *Work. Pap., Grantham Research Institute on Climate Change and the Environment*, 2012.

S. Dynarski. The new merit aid. In *College choices: The economics of where to go, when to go, and how to pay for it*, pages 63–100. University of Chicago Press, 2004.

D. Hoechle. Robust standard errors for panel regressions with cross-sectional dependence. *The Stata Journal*, 7(3):281–312, 2007.

B. Lin and X. Li. The effect of carbon tax on per capita co 2 emissions. *Energy policy*, 39 (9):5137–5146, 2011.

Q. Liu, Y. Chen, C. Tian, X. Zheng, F. Teng, A. Gu, X. Yang, X. Wang, E. Matthews, and R. Song. Peaking china's co2 emissions: Trends and mitigation potential. 2015.

S. Meng, M. Siriwardana, and J. McNeill. The environmental and economic impact of the carbon tax in australia. *Environmental and Resource Economics*, pages 1–20, 2013.

R. G. Newell, W. A. Pizer, and D. Raimi. Carbon markets 15 years after kyoto: Lessons learned, new challenges. *The Journal of Economic Perspectives*, 27(1):123–146, 2013.

F. Scrimgeour, L. Oxley, and K. Fatai. Reducing carbon emissions? the relative effectiveness of different types of environmental tax: the case of new zealand. *Environmental Modelling & Software*, 20(11):1439–1448, 2005.

R. Song, W. Dong, J. Zhu, X. Zhao, and Y. Wang. Assessing implementation of china's climate policies in the 12th 5-year period. *World Resources Institute, September*, 2015.

G. A. Tanguay, P. Lanoie, and J. Moreau. Environmental policy, public interest and political market. *Public Choice*, 120(1):1–27, 2004.

G. Y. Zakarya, B. Mostefa, S. M. Abbes, and G. M. Seghir. Factors affecting co2 emissions in the brics countries: a panel data analysis. *Procedia Economics and Finance*, 26: 114–125, 2015.

A Appendix I. Definitions and measures

The main terms in this articles are listed as follows.

Eenergy Intensity (EI) $= \frac{\text{Total primary energy consumption}}{\text{Population}*\text{Total GDP}}$

Total primary energy consumption = Total renewable energy consumptionTotal non-renewable energy consumption

Share of each energy consumption $= \frac{\text{Consumption of each energy}}{\text{Total primary energy consumption}}$

$CO2_{it}$: carbon dioxide emissions per capita per year from fossil fuel use and cement production excluding short-cycle biomass burning (for example, agricultural waste burning) and excluding large-scale biomass burning (for example, forest fires) (Million ton CO2 per year)

GDP on PPP: gross domestic product based on purchasing-power-parity (PPP) valuation of country GDP (Current international dollar, Billions)

GDP: gross domestic product, current prices (U.S. dollars , Billions)

Coal consumption: commercial solid fuels only, i.e. bituminous coal and anthracite (hard coal), and lignite and brown (sub-bituminous) coal, and other commercial solid fuels. Excludes coal converted to liquid or gaseous fuels, but includes coal consumed in transformation processes. (Million tonnes oil equivalent)

Natural gas consumption: Excludes natural gas converted to liquid fuels but includes derivatives of coal as well as natural gas consumed in Gas-to-Liquids transformation. (Million tonnes oil equivalent)

Hydroelectricity consumption: Based on gross primary hydroelectric generation and not accounting for cross-border electricity supply. Converted on the basis of thermal equivalence assuming 38% conversion efficiency in a modern thermal power station. (Million tonnes oil equivalent)

Consumption of nuclear, solar, wind, and geothermal, biomass and other waste: Based on gross generation and not accounting for cross-border electricity supply. Converted on the basis of thermal equivalence assuming 38% conversion efficiency in a modern thermal power station. (Million tonnes oil equivalent)

B Appendix II. Test for the choice of covarites

We first regress on share of each energy consumption on carbon taxation dummy, Energy Intensity and GDP on PPP per capita. The results are shown in Table (A.1). Next, we regress on share of each energy consumption on the interaction of carbon taxation and ETS, Energy Intensity and GDP on PPP per capita. The results are shown in Table (A.2).

Table A.1:

We regress on share of each energy consumption on carbon taxation dummy, Energy Intensity and GDP on PPP per capita.

	REGRESSIONS							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
VARIABLES	share_geoth	share_solar	share_wind	share_nuclear	share_coal	share_hydro	share_natgas	share_oil
tax_dummy	0.010	-0.001	0.006	-0.001	-0.009	0.000	0.003	-0.009
	(-0.004 - 0.025)	(-0.003 - 0.001)	(-0.011 - 0.023)	(-0.021 - 0.019)	(-0.048 - 0.030)	(-0.008 - 0.008)	(-0.036 - 0.043)	(-0.053 - 0.035)
EI_gdp_pc	-0.123*	-0.003	-0.068	0.254*	-0.432	0.187	-0.062	0.248
	(-0.264 - 0.018)	(-0.040 - 0.033)	(-0.201 - 0.064)	(-0.046 - 0.555)	(-1.192 - 0.328)	(-0.172 - 0.545)	(-0.727 - 0.603)	(-0.971 - 1.467)
gdp_ppp_pc	-0.001**	-0.000**	-0.001*	0.000	-0.002	0.001	-0.001	0.004
	(-0.002 - -0.000)	(-0.000 - -0.000)	(-0.002 - 0.000)	(-0.001 - 0.001)	(-0.006 - 0.003)	(-0.001 - 0.002)	(-0.005 - 0.002)	(-0.003 - 0.011)
Observations	910	910	910	910	910	910	910	910
Country FE	yes	yes	yes	yes	yes	yes	yes	yes
Year FE	yes	yes	yes	yes	yes	yes	yes	yes

Robust ci in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table A.2:

We regress on share of each energy consumption on carbon taxation X ETS, Energy Intensity and GDP on PPP per capita.

	REGRESSIONS							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
VARIABLES	share_geoth	share_solar	share_wind	share_nuclear	share_coal	share_hydro	share_natgas	share_oil
taxXets_dummy	0.011	-0.003**	0.008	-0.000	-0.013	0.004	-0.019	0.011
	(-0.002 - 0.025)	(-0.005 - -0.000)	(-0.015 - 0.032)	(-0.017 - 0.016)	(-0.054 - 0.029)	(-0.004 - 0.011)	(-0.053 - 0.015)	(-0.031 - 0.053)
EI_gdp_pc	-0.124	-0.004	-0.068	0.255*	-0.433	0.189	-0.076	0.261
	(-0.276 - 0.028)	(-0.041 - 0.033)	(-0.198 - 0.062)	(-0.048 - 0.558)	(-1.191 - 0.325)	(-0.167 - 0.545)	(-0.760 - 0.608)	(-0.971 - 1.493)
gdp_ppp_pc	-0.001**	-0.000**	-0.001*	0.000	-0.002	0.001	-0.001	0.004
	(-0.002 - -0.000)	(-0.000 - -0.000)	(-0.002 - 0.000)	(-0.001 - 0.001)	(-0.006 - 0.003)	(-0.001 - 0.002)	(-0.004 - 0.002)	(-0.003 - 0.010)
Observations	910	910	910	910	910	910	910	910
Country FE	yes	yes	yes	yes	yes	yes	yes	yes
Year FE	yes	yes	yes	yes	yes	yes	yes	yes

Robust ci in parentheses

*** $p<0.01$, ** $p<0.05$, * $p<0.1$